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Non Ruminant Nutrition

Evaluation of essential fatty acids in lactating sow diets on sow reproductive performance, colostrum and milk composition, and piglet survivability

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Abstract

Mixed parity sows (n = 3,451; PIC, Hendersonville, TN; parities 2 through 9) and their litters were used to evaluate the effects of essential fatty acid (EFA) intake on sow reproductive performance, piglet growth and survivability, and colostrum and milk composition. Our hypothesis, like observed in earlier research, was that increasing linoleic acid (LA) and α-linolenic acid (ALA) would improve sow and litter performance. At approximately day 112 of gestation, sows were randomly assigned within parity groups to 1 of 4 corn–soybean meal–wheat-based lactation diets that contained 0.5 (Control) or 3% choice white grease (CWG), 3% soybean oil (SO), or a combination of 3% soybean oil and 2% choice white grease (Combination). Thus, sows were provided diets with low LA and ALA in diets with CWG or high LA and ALA in diets that included soybean oil. Sows received their assigned EFA treatments until weaning and were then fed a common gestation and lactation diet in the subsequent reproductive cycle. Average daily feed intake during the lactation period increased ($P < 0.05$) for sows fed the Combination and CWG diets compared with sows fed the Control or SO diet. However, daily LA and ALA intakes of sows fed the Combination and SO diets were still greater ($P < 0.05$) than those of sows fed 0.5 or 3% CWG. Overall, sows consuming high EFA from the Combination or SO diets produced litters with heavier ($P < 0.05$) piglet weaning weights and greater ($P < 0.05$) litter ADG when compared with litters from sows fed diets with CWG that provided low EFA. Despite advantages in growth performance, there was no impact of sow EFA intake on piglet survivability ($P > 0.10$). Additionally, lactation diet EFA composition did not influence sow colostrum or milk dry matter, crude protein, or crude fat content ($P > 0.10$). However, LA and ALA content in colostrum and milk increased ($P < 0.05$) in response to elevated dietary EFA from SO. There was no evidence for differences ($P > 0.10$) in subsequent sow reproductive or litter performance due to previous lactation EFA intake. In conclusion, increased LA and ALA intake provided by soybean oil during lactation increased overall litter growth and pig weaning weights, reduced sow ADFI, but did not affect piglet survivability or subsequent performance of sows.

Lay Summary

Supplemental fat sources are an effective and widely accepted strategy to increase energy density of sow lactation diets that can also provide essential fatty acids such as linoleic acid (LA) and α-linolenic acid (ALA). Currently, the effects of supplemental LA and ALA provided shortly before farrowing on colostrum and milk composition are not fully understood. Additionally, the influence of elevated LA and ALA provided in sow lactation diets on litter growth and survivability responses has not been extensively evaluated. Therefore, this trial was conducted to evaluate the effects of fat sources providing low and high LA and ALA intake on sow performance, litter growth and survivability, colostrum and milk composition, and subsequent reproductive performance. Overall, sows consuming diets with high LA and ALA provided by soybean oil produced litters with heavier piglet weaning weights and greater litter average daily gain when compared with sows consuming diets with low LA and ALA content. Increasing LA and ALA by added soybean oil also increased their content in colostrum and milk. However, there was no influence of sow LA and ALA intake on litter survivability or subsequent reproductive performance of sows.

Key words: α-linolenic acid; essential fatty acids; lactation; linoleic acid; piglet survivability; sow

Abbreviations: AA, amino acid; ADFI, average daily feed intake; ADG, average daily gain; ALA, α-linolenic acid; ARA, arachidonic acid; BW, bodyweight; CP, crude protein; CWG, choice white grease; DHA, docosahexaenoic acid; EFA, essential fatty acid; EPA, eicosapentaenoic acid; LA, linoleic acid; ME, metabolizable energy; PUFA, polyunsaturated fatty acids; SBM, soybean meal; SID, standardized ileal digestible; SO, soybean oil

Introduction

Nutrient requirements for the modern lactating sow must be met to support milk production and nutrient output for the growth and development of larger and heavier litters. However, sows often do not consume enough feed during lactation to meet nutrient intake requirement estimates (Tokach et al., 2019). Utilization of supplemental fat sources is an effective and widely accepted strategy to increase energy density of sow lactation diets that can also provide essential fatty acids (EFA) such as linoleic acid (LA) and α-linolenic acid (ALA) that cannot be synthesized by the sow. EFA support neonatal brain, vision, and immune system development and

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function (Kaur et al., 2014). The two parental EFA (LA and ALA) may be elongated to form other polyunsaturated fatty acids (PUFA) such as arachidonic acid (ARA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) that serve as precursors for prostaglandins that regulate inflammatory responses (Ricotti and FitzGerald, 2011) and reproductive function (Roszkos et al., 2020). The NRC (2012) currently suggests 6.0 g/d LA intake for sows, but specific requirements for ALA intake for the prolific sow are not currently available.

Previously, researchers have observed alterations in milk fat or fatty acid composition as a reflection of dietary fatty acid composition when supplemented in mid- to late gestation (Lauridsen and Danelsen 2004; Jin et al., 2017). However, the influences of supplemental fat source and EFA content on colostrum and milk composition provided shortly prior to farrowing are not fully understood. The primary route of EFA excretion is through the sow's milk and thus, changes in EFA intake even shortly prior to farrowing could influence colostrum and milk EFA composition that may impact litter growth performance and survivability.

Rosero et al. (2015) concluded that sows remaining in a negative EFA balance may enter a state of deficiency that impairs subsequent reproductive function and later suggested that dietary EFA intake should exceed 125 g/d of LA and 10 g/d of ALA to maximize reproductive performance (Rosero et al., 2016a). Additionally, Australian Pork Ltd (van Wettere, 2018) observed a reduction in piglets born dead when sows were fed diets containing 120 g/d LA compared with 70 g/d of LA beginning at entry to the farrowing room. However, the influence of elevated LA and ALA intake in sow lactation diets on litter growth and survivability responses has not been extensively evaluated. Therefore, the objective of this study was to determine the influence of fat source providing low and high EFA intake on sow performance, litter growth and survivability, colostrum and milk composition, and subsequent reproductive performance.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment (Protocol 4423). This experiment was conducted at a commercial sow research facility in Utah (Smithfield Foods Inc., Milford, UT) between August 2020 and July 2021.

Animals, housing, and treatments

A total of 3,451 mixed-parity sows (parity, 4.8 ± 1.8; initial BW, 250.3 ± 26.6 kg; PIC, Hendersonville, TN) were used in this experiment. On approximately day 112 of gestation, sows were blocked by parity within farrowing room and randomly assigned to 1 of 4 dietary treatments. Lactation diets were pelleted corn–soybean meal–wheat-based and included supplemental fat as either 0.5 (Control) or 3% choice white grease (CWG), 3% soybean oil (SO), or a combination of 3% soybean oil and 2% choice white grease (Combination). For the Control treatment, 0.5% added fat was included for pelleting purposes. Thus, sows were provided diets with low and high EFA and were projected to have daily EFA intakes as follows: Control: 89 g/d LA and 5 g/d ALA; CWG: 109 g/d LA and 6 g/d ALA; SO: 189 g/d LA and 19 g/d ALA; and Combination: 205 g/d LA and 20 g/d ALA (assumed 6.3 kg ADFI). All diets were formulated to meet or exceed NRC (2012) requirement estimates with a constant SID Lys:ME ratio for all diets at 3.22 g/Mcal with SID Lys increasing from 1.07% to 1.14% as dietary fat increased (Table 1). Approximately 5 d prior to farrowing, sows were provided 1.8 kg/d of their assigned lactation diet and then allowed ad libitum access after parturition. Throughout the lactation period, individual sow feed intake was monitored by recording daily feed additions and weighing remaining feed at weaning. Primiparous sows were not utilized in this study.

During feed manufacturing, soybean oil was added to the mixer for incorporation into SO and Combination treatments and choice white grease was sprayed on pellets after mixing of complete diets. All diets were manufactured in pelleted form for the duration of the experimental period and the average percentage of pellet fines for each treatment were as follows: Control, 11.2%; CWG, 13.1%; SO, 18.3%; and Combination, 21.5%.

At entry to the farrowing rooms and at weaning, sow bodyweight (BW) and backfat depth were recorded. Backfat measures were completed with ExaGo (BioTronics Inc., Ames, IA, USA) at the last rib position approximately 6 to 8 cm from the midline. Each farrowing stall (2.39 × 1.70 m) contained a nipple waterer and feeder for the sow.

Litter size was standardized through cross-fostering of pigs within treatment within 24 h of parturition. Count of pigs born alive, stillborn, and mummified and litter weights of pigs born alive were recorded for each sow. Additionally, all stillborn and mummified pigs were weighed and recorded within litter. Litters were weighed again at 24 h after cross-fostering and 1 d prior to weaning to determine litter growth performance. All instances and reasons for piglet mortalities were recorded. Total pigs born per litter was calculated as the sum of pigs born alive, stillborn, and mummified. Litter survivability from birth to 24 h was calculated as: [(Pigs born alive – count of mortality within 24 h)/pigs born alive]. Litter survivability from 24 h to weaning was calculated as: (count of pigs at weaning/count of pigs alive at 24 h).

Within 3 h of the onset of parturition, colostrum was collected from a subset of 40 sows (*n*, 10 sows/treatment) by hand stripping all functional teats, with an attempt to collect equal volumes from all teats for one representative sample. One day prior to weaning, milk samples were also collected as previously described. To initiate milk letdown at weaning, 10 IU of oxytocin was administered via intramuscular injection. All samples were immediately frozen and stored at –20 °C until analysis.

At weaning, sows were moved to individual gestation stalls and checked daily for signs of estrus. Wean to first service interval and the percentage of sows bred by days 7 and 12 were recorded on the 2,938 sows that remained after culling. Farrowing rate and subsequent farrowing performance including total born, born alive, stillborn, and mummified were also evaluated. During the subsequent performance period, all sows consumed a common gestation and lactation diet that contained 0.5% choice white grease.

Chemical analysis

Diet samples were collected once weekly, pooled by month (*n*, 6 per treatment), and stored at –20 °C before submission to commercial laboratories for proximate and fatty acid profile analysis (Midwest Labs, Omaha, NE; and University of Missouri, ESCL, Columbia, MO, respectively; Table 2). Standard procedures (AOAC International, 2006) were followed for analysis of moisture (method 934.15), crude

Table 1. Diet composition (as-fed basis)[1]

Item	Control	CWG	SO	Combination
Ingredient, %				
Corn	42.69	37.87	37.67	33.98
Soybean meal (47% CP)	27.45	29.50	29.85	31.50
Wheat, soft white	25.00	25.00	25.00	25.00
Choice white grease	0.50	3.00	—	2.00
Soybean oil	—	—	3.00	3.00
Calcium carbonate	1.10	1.10	1.10	1.10
Monocalcium phosphate (21% P)	1.15	1.25	1.25	1.30
Salt	0.50	0.55	0.55	0.55
Liquid Lys 50%	0.38	0.36	0.36	0.34
Liquid Met 88%	0.05	0.05	0.05	0.05
L-Thr	0.07	0.07	0.07	0.07
Choline chloride 60%	0.05	0.05	0.05	0.05
Trace mineral premix[2]	0.12	0.12	0.12	0.12
Vitamin premix[3]	0.06	0.06	0.06	0.06
Miscellaneous[4]	0.88	1.02	0.87	0.88
Total	100.00	100.00	100.00	100.00
Calculated analysis				
SID AA, %				
Lys	1.03	1.07	1.07	1.10
Ile:Lys	68	71	72	74
Met:Lys	29	30	30	30
Met and Cys:Lys	56	57	57	58
Thr:Lys	66	68	69	70
Trp:Lys	20	21	21	22
Val:Lys	77	80	81	83
ME, kcal/kg	3,197	3,296	3,327	3,413
SID Lys:ME, g/Mcal	3.22	3.22	3.22	3.22
CP, %	19.2	19.8	19.9	20.4
Crude fat, %	2.58	4.92	4.91	6.79
Ca, %	0.70	0.73	0.73	0.74
Available P,%	0.41	0.43	0.43	0.44
Linoleic acid, %	1.29	1.38	2.79	2.87
α-Linolenic acid, %	0.07	0.08	0.38	0.39

[1]Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).
[2]Guaranteed analysis of premix: 12.00% Zn; 12.00% Fe; 4.00% Mn; 1.60% Cu; 0.032% I; 0.024% Se.
[3]Provided per kg of premix: 16,664,903 IU vitamin A; 2,333,333 IU vitamin D3; 166,667 IU vitamin E; 52.9 mg vitamin B12; 6,333 mg menadione; 13,333 mg riboflavin; 50,000 mg pantothenic acid; 4,000 mg thiamine; 60,000 mg niacin; 8,000 mg vitamin B6; 6,000 mg folic acid; 866.7 mg biotin; 267 mg chromium.
[4]Includes laxative product, flow agent, and dye coloring for treatment identification

protein (method 990.03), ether extract (method 2003.05), ash (method 942.05), and fatty acid profiles (method 996.06). Analysis of crude fiber was completed according to the AOCS (2017) approved procedure (method Ba 6a-05).

Additionally, colostrum and milk samples were sent to a commercial laboratory for analysis of moisture (method 934.01), crude protein (method 990.03), ether extract (method 920.39), and fatty acid profiles (method 996.06; University of Missouri ESCL, Columbia, MO).

Statistical analysis

Data were analyzed using the GLIMMIX procedure in SAS (Version 9.4, SAS Institute, Inc., Cary, NC) and considered sow (litter) as the experimental unit. The statistical model considered fixed effects of dietary treatment and random effects of farrowing room. The following response criteria were fitted with a Poisson distribution in the statistical model: parity, functional teats, and litter size at farrowing, start, and weaning. The percentage of pigs born alive, stillborn, and mummified, survival of pigs from birth to 24 and from 24 h to wean, percentage of sows bred by days 7 and 12, and farrowing rate were fitted by a binomial distribution in the statistical model. All other response criteria were fit using a normal distribution. A total of 4,036 sows were enrolled in the experiment at the initial allotment; however, any sow that did not complete a full lactation period was removed from the final dataset prior to analysis (*n*, 344 sows; Table 3). Reasons for early lactation removal included sow prolapses, early

weaning, and mortalities. Additionally, nurse sows and sows with mixed litters after cross-fostering (situations where pigs from more than one treatment were placed within a litter) were removed from the final dataset (*n*, 241 sows). Therefore, the final dataset contained data collected from 3,451 sows (Table 4). Data are reported as least square means and considered statistically significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results and Discussion

Sow performance and litter survivability

As expected, average parity, days of pre-farrow lactation diet consumption, lactation length, and count of functional teats per sow were similar across experimental treatments ($P > 0.10$; Table 5). Although there was no evidence for differences among sow BW when sows entered the farrowing rooms at

Table 2. Chemical analysis of diets (as-fed basis)[1,2]

Item, %	Control	CWG	SO	Combination
DM	87.28	87.26	87.88	87.77
CP	19.6	19.8	20.0	20.6
Crude fat	2.53	4.76	4.84	6.52
Acid detergent fiber	3.09	3.11	3.00	3.14
Ash	5.42	5.59	5.57	5.65
Linoleic acid[3]	1.25	1.54	2.64	2.88
α-Linolenic acid[3]	0.09	0.12	0.35	0.39

[1]Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). Diet samples were collected once weekly and pooled by month prior to analysis. Values represent the average analyzed composition from 6 samples collected between August 2020 to February 2021.
[2]Proximate analysis was completed by Midwest Laboratories (Omaha, NE).
[3]Fatty acid profile analysis was completed by the University of Missouri Experiment Station Chemical Laboratories (Columbia, MO).

Table 3. Reasons for sow removal and mortality[1,2]

Reason	Control	CWG	SO	Combination
Early weaned sows[3]	34	25	25	29
Prolapse				
Vaginal/uterine	13	17	15	14
Rectal	3	7	4	10
Uncategorized	6	2	3	2
Sow mortality				
Euthanized[4]	15	7	7	9
Sudden death	24	16	18	27
Unknown	3	3	4	2
Total	98	77	76	93

[1]Sows were removed from the final dataset due to incompletion of full lactation period.
[2]Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).
[3]Reasons for early wean include small litter size, inability to milk/low functional teats, and illness.
[4]Reasons for euthanasia include difficulty farrowing, retained pigs, lameness, injured, and downer sows.

Table 4. Parity distribution of sows within experimental treatments[1]

Parity	Control	CWG	SO	Combination	Total
2	96	86	90	90	362
3	80	118	108	93	399
4	214	205	201	207	827
5	200	192	188	192	772
6	128	131	125	121	505
7	46	40	64	78	228
8	51	60	56	56	223
9	35	33	42	25	135
Total	850	865	874	862	3,451

[1]Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

Table 5. Effects of dietary fat source and essential fatty acid intake on lactating sow performance[1]

Trait	Control	CWG	SO	Combination	SEM	*P*
Sows, n	850	865	874	862	—	—
Parity	4.7	4.7	4.7	4.7	0.11	0.858
Pre-farrow days	4.6	4.6	4.6	4.6	0.12	0.528
Lactation length, d	24.1	24.1	24.0	24.1	0.11	0.733
Functional teats	14.9	14.9	14.9	14.9	0.13	0.999
Sow BW, kg						
d 112 gestation	248.6	249.7	249.0	249.1	1.29	0.832
Wean	242.9	243.9	244.5	244.8	1.41	0.478
Change	−5.7[b]	−5.7[b]	−4.5[ab]	−4.1[a]	0.83	0.090
Sow backfat, mm						
d 112 gestation	12.2	12.3	12.3	12.0	0.13	0.219
Wean	12.1[a]	12.1[a]	12.0[a]	11.7[b]	0.12	0.046
Change	−0.20	−0.17	−0.25	−0.22	0.085	0.857
Sow ADFI, kg						
Pre-farrow	1.81	1.81	1.81	1.81	0.001	0.546
Lactation	6.64[b]	6.83[a]	6.57[b]	6.88[a]	0.039	<0.001
Lactation EFA intake, g/d						
Linoleic acid[2]	83.0[d]	105.1[c]	173.6[b]	198.4[a]	0.83	<0.001
α-linolenic acid[2]	6.0[d]	8.2[c]	23.0[b]	26.9[a]	0.10	<0.001
Total EFA[2]	88.9[d]	112.6[c]	196.6[b]	225.3[a]	0.93	<0.001
Farrowing performance						
Total pigs born, n	15.6	15.5	15.7	15.8	0.14	0.481
Pigs born alive, %	88.4[a]	88.3[ab]	87.9[ab]	87.4[b]	0.34	0.033
Stillborn,%	8.9[b]	9.4[ab]	9.4[ab]	10.2[a]	0.30	0.003
Mummy, %	2.6	2.3	2.7	2.4	0.15	0.276
Litter survivability, %						
Birth to 24 h[3]	89.9	89.1	89.3	89.6	0.33	0.167
24 h to wean[4]	89.7	90.0	90.0	89.6	0.33	0.751

[a-d]Means within row with different superscripts differ ($P < 0.05$).
[1]A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).
[2]Calculated using analyzed LA and ALA values and overall lactation ADFI.
[3]Survival from birth to 24 h, [(pigs born alive – count of mortality within 24 h)/pigs born alive].
[4]Survival from 24 h to wean, count of pigs at weaning/count of pigs alive at 24 h.

day 112 of gestation or at weaning ($P > 0.10$), sows that consumed the Combination diet with 5% added fat tended (P 0.090) to lose less BW during the lactation period compared to sows consuming diets with either 0.5 or 3% CWG, with sows fed SO intermediate. Although variation in the effects of increasing supplemental lipids among studies exists, a review by Rosero et al. (2016a) suggests that increased daily calorie intake of lipid-fed sows reduced sow BW loss by 1.0 kg during lactation, which aligns with the results observed in the present study.

There was no evidence of difference ($P > 0.10$) in sow backfat thickness at entry to the farrowing room among experimental treatments. However, sows fed the Combination diet exhibited less backfat depth at weaning compared with all other treatments (P 0.046). As stated in the NRC (2012), maternal protein and lipids are mobilized to provide a source of energy when maintenance energy and milk production requirements are not supported by dietary energy intake alone. However, the overall change in backfat depth of sows from day 112 of gestation to weaning was similar across dietary treatments ($P > 0.10$).

Controlled feed offerings prior to farrowing resulted in similar pre-farrow ADFI across dietary treatments ($P > 0.10$). Overall, lactation daily feed intake was greater when sows were fed the Combination and CWG diets compared with sows consuming the Control and SO diets ($P < 0.001$). Rosero et al. (2012) observed similar ADFI among sows fed CWG in comparison to diets without added fat, whereas sows provided diets with an animal-vegetable blend had greater ADFI. Regardless of the fat source, increasing supplemental fat also increased daily energy intake. In contrast, however, Xue et al. (2012) observed increased then reduced ADFI and daily energy intake as supplemental fat within lactation diets increased.

Despite reduced feed intake, sows provided SO diets still consumed greater ($P < 0.001$) daily intakes of LA and ALA than sows fed the Control and CWG diets. Currently, the NRC (2012) indicates that lactating sows should consume at least 6 g/d of LA, but recommendations for ALA intake are not stated. From a review conducted by Rosero et al. (2016a), it is suggested that sows consume at least 125 g/d of LA and 10 g/d of ALA to mitigate a negative EFA balance during lactation and maximize reproductive efficiency. Daily LA and

ALA intakes of sows within the current study for the SO and Combination dietary treatments exceeded the recommended LA and ALA intakes from Rosero et al. (2016a), whereas diets containing choice white grease at 0.5% or 3% did not.

The count of pigs born per litter and percentage of mummified pigs were not influenced ($P > 0.10$) by dietary treatments provided approximately 5-d prior to farrowing. However, the percentage of pigs born alive decreased when sows were provided diets with high EFA and added dietary fat at 5% when compared with sows provided low EFA and 0.5% added fat within the Control treatment, with sows provided dietary fat at 3% as either CWG or SO intermediate ($P < 0.05$). This response was supported by the greater percentage of stillborn pigs per litter among sows provided the Combination treatment compared with the Control, with sows provided CWG and SO intermediate ($P < 0.005$). Although feed intake was similar across treatments prior to farrowing, sows consumed 5.8 to 6.2 Mcal/d ME when provided diets with added fat. However, it was not expected that dietary treatments provided to sows approximately 5-d pre-farrow would influence stillborn rate.

Overall, there was no influence ($P > 0.10$) of sow lactation treatments on litter survivability from birth to 24 h or from 24 h to weaning. Available literature regarding the influence of supplemental fat and dietary n-3 and n-6 PUFA content on litter survivability are variable. In contrast to the current study, improved preweaning survivability of piglets has been observed when sows were provided supplemental fat sources with elevated n-6 and n-3 PUFA provided by soybean oil or with increased n-3 PUFA alone provided through fish oils (Rooke et al., 2001; Quiniou et al., 2008; Farmer et al., 2010; Jin et al., 2017; Lavery et al., 2019). Others, however, were not able to detect any influence of fat source or EFA content on piglet survivability (Mateo et al., 2009; Rosero et al., 2012). Furthermore, effects of n-3 PUFA through utilization of fish oils that provide high concentrations of DHA and EPA in gestation and lactation diets has been evaluated, but with inconsistent responses on litter survivability (Tanghe and Smet, 2013; Roszkos et al., 2020). This variation is likely due to differences among oil sources, inclusion rates, timing of pre-farrow supplementation, and basal population mortality rates across studies. Furthermore, consideration of type 2 errors due to insufficient treatment replication to evaluate litter survivability differences across studies may be warranted. In the present study, 850 to 874 replications per treatment should have been sufficient to support evaluation of true litter survivability differences if present.

The larger litter size of modern sows increases the potential for oxidative stress, especially in late gestation and lactation (Berchieri-Ronchi et al., 2011; Liu et al., 2018). Dietary oils that stimulate production of anti-inflammatory compounds and reduce oxidative stress can positively influence both sow performance and litter survival (Ward et al., 2020). Plant oil sources provide rich amounts of the parental n-3 and n-6 fatty acids that serve as precursors for conversion to long-chain PUFA. ALA can be converted to DHA and EPA, which are present in high concentrations within fish oils, and LA can be converted to ARA. These long chain PUFA can be provided through direct dietary consumption or from de novo synthesis from the parental ALA or LA. However, conversion efficiency may be limited, as desaturase enzymes are shared among the EFA (Lauridsen and Danielsen, 2004). Although conversion efficiency may be limited between LA and ALA, long-chain PUFA incorporated into cell membranes can influence gastrointestinal health and function and inflammatory immune response (Calder, 2003, 2013; Farmer et al., 2010; Leonard et al., 2011; Peng et al., 2019; Lauridsen, 2020). In the present study, n-6:n-3 ratios among experimental treatments were not considered in diet formulation, however, n-6:n-3 ratios ranged from 18:1, 17:1, 7:1, and 7:1 across the Control, CWG, SO, and Combination treatments, respectively.

Litter growth performance

There was no evidence for difference ($P > 0.10$) in litter or average piglet weights at birth or 24 h after birth (Table 6). However, sows fed diets with high EFA provided in the Combination and SO diets produced litters with greater ($P < 0.05$) total litter gain and litter ADG during lactation. This response supported heavier litter weaning weights for sows with high LA and ALA daily intake when compared with litters from sows provided low EFA in diets containing choice white grease at 0.5 or 3%. These litter growth responses mirrored heavier piglet weaning weights and piglet ADG ($P < 0.001$) for litters from sows fed the Combination and SO diets when compared with litters from sows fed diets with low EFA provided through choice white grease.

To support milk production for improved growth of larger litter sizes, elevated lactation feed intake, mobilization of sow body reserves, or both must occur (Strathe et al., 2017). In the present study, sows provided CWG and Combination fat diets had greater ADFI than sows provided SO or 0.5% supplemental fat in the Control diet. However, litter ADG between SO and Combination treatments were similar despite differences in sow ADFI and EFA intake. It is possible that the influence of increased ME in the Combination treatment supported enhanced litter growth (Park et al., 2008); however, the positive impacts of added fat on litter growth are not always observed (Rosero et al., 2012). Therefore, we speculate that the elevated LA and ALA intake provided to sows with the SO and Combination treatments is the reason for their greater litter performance.

EFAs are primarily secreted in milk of the lactating sow to support litter growth and development (Innis, 2007; Odle et al., 2014). In review of the literature, many studies did not observe an influence of increased n-3 and/or n-6 PUFA provided to sows in late gestation through lactation on litter gain (Fritsche et al., 1993; Lauridsen and Jensen, 2007; Leonard et al., 2011; Smits et al., 2011; Rosero et al., 2016b; Lavery et al., 2019; McDermott et al., 2020). Others that supplemented fish oils rich in n-3 PUFA or soybean oil rich in both n-3 and n-6 PUFA did detect an improvement in litter growth during lactation (Lauridsen and Danielsen, 2004; Mateo et al., 2009; Luo et al., 2013; Jin et al., 2017). It is difficult to clearly distinguish the cause for discrepancy across studies in this area. However, the lack of responses in some studies could be due to low inclusion levels of oil sources, comparison of oil sources with similar PUFA profiles, or limited treatment replication within experiments.

Colostrum and milk composition

Supplemental fat source and EFA composition did not influence ($P > 0.10$) crude protein, or crude fat content in colostrum or milk at weaning (Tables 7 and 8). Previously, researchers have observed greater colostrum and milk fat output when lactating sows consumed diets with increased energy density provided by supplemental lipids (Tilton et al., 1999; Park et al., 2008; Farmer and Quesnel, 2009; Rosero et al., 2015; Peng et al., 2019). Furthermore, others have

Table 6. Effects of dietary fat source and essential fatty acid intake on litter performance[1]

Trait	Control	CWG	SO	Combination	SEM	*P*=
Sows, *n*	850	865	874	862	—	—
Litter size, *n*						
Start[2]	12.5	12.5	12.4	12.4	0.12	0.996
Wean	11.2	11.2	11.2	11.2	0.11	0.995
Litter weight, kg						
Total born	20.4	20.3	20.3	20.5	0.17	0.677
Born alive	18.7	18.5	18.5	18.5	0.16	0.881
Start[2]	17.7	17.7	17.7	17.6	0.13	0.528
Wean	75.5[b]	76.5[ab]	77.1[a]	77.3[a]	0.62	0.028
Litter gain, kg[3]	57.8[b]	58.7[ab]	59.4[a]	59.7[a]	0.56	0.006
Litter ADG, kg[4]	2.46[b]	2.51[ab]	2.54[a]	2.55[a]	0.020	0.003
Piglet bodyweight, kg						
Total born	1.34	1.33	1.33	1.33	0.009	0.606
Born alive	1.38	1.37	1.37	1.37	0.009	0.689
Start[2]	1.42	1.42	1.43	1.42	0.008	0.620
Wean	6.72[b]	6.79[b]	6.88[a]	6.90[a]	0.045	<0.001
Piglet ADG, kg[5]	0.218[c]	0.222[b]	0.225[a]	0.227[a]	0.0016	<0.001

[a-c]Means within row with different superscripts differ ($P < 0.05$).

[1]A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).
[2]Start litter size represents litter size within 24 h of farrowing after cross-fostering within treatment.
[3]Litter gain, litter weight at wean – litter weight at start.
[4]Litter ADG, litter gain ÷ lactation length.
[5]Piglet ADG, litter ADG ÷ count of pigs at wean.

Table 7. Effects of dietary fat source and essential fatty acid intake on colostrum composition[1]

Trait	Control	CWG	SO	Combination	SEM	*P*
Crude protein, %	16.8	16.6	17.1	18.2	0.95	0.584
Crude fat, %	4.2	4.4	4.5	3.9	0.46	0.697
Fatty acid profile, %[2]						
14:0	1.35	1.28	1.22	1.29	0.065	0.590
16:0	21.74	21.19	20.93	20.80	0.373	0.287
16:1n-9	2.90	3.03	2.63	2.55	0.183	0.227
18:0	5.43	5.35	5.21	5.07	0.234	0.704
18:1n-9	33.00[a]	33.08[a]	31.18[a]	28.78[b]	0.836	< 0.001
18:2n-6	23.06[b]	23.29[b]	26.04[ab]	28.45[a]	1.176	0.003
18:3n-3	1.02[b]	1.13[b]	1.69[a]	1.91[a]	0.143	< 0.001
20:4n-6	1.13	1.10	1.19	1.13	0.057	0.720
20:5n-3	0.056[c]	0.068[bc]	0.080[a]	0.077[ab]	0.005	0.004
22:6n-3	0.047	0.049	0.045	0.049	0.003	0.678
Other[3]	8.01	8.18	7.64	7.68	0.193	0.140

[ab]Means within row with different superscripts differ ($P < 0.05$).
[1]A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). A subset of 10 sows per treatment were randomly selected for analysis of colostrum composition.
[2]Represented as a percentage of total colostrum fat.
[3]Contains 2% or less of the following: 14:1, 15:0, 17:0, 17:1, 18:1*t*, 18:2*t*, 18:3n-6, 20:0, 20:2, 21:0, 22:0, 23:0, 24:0, and unidentifiable fatty acids.

suggested that milk fat content may contribute to improved litter growth performance and preweaning litter survivability (Pettigrew, 1981; Bontempto and Jiang, 2015; Jin et al., 2017). However, similar to the current study, others did not distinguish an impact of supplemental fat in lactation diets on milk fat concentrations (Lauridsen and Danielson, 2004; Llaurado-Calero et al., 2021).

The similarity in milk fat content among treatments in the present study would argue that improved litter growth may not be due to macronutrient composition of colostrum

and milk alone, but rather EFA composition or increased milk production. Regardless of similarities within colostrum fat content in the current study, colostrum LA (C18:2n-6) and ALA (C18:3n-3) increased ($P < 0.05$) in response to the increased EFA composition of diets that contained soybean oil. Additionally, sows provided SO prior to farrowing produced colostrum with a greater proportion of EPA (C20:5n-3) compared with sows provided diets with low EFA ($P < 0.005$). However, EFA intake did not influence the proportion of DHA within colostrum ($P > 0.05$).

As observed in the present study, fatty acid composition of milk is highly influenced by dietary fatty acid composition (Tilton et al., 1999; Lauridsen and Danielsen, 2004). Additionally, modifications to dietary EFA composition or alteration of sow EFA intake prior to parturition can impact colostrum LA and ALA (Yao et al., 2012; Decaluwe et al., 2014). Therefore, it was not surprising that the modifications in colostrum EFA composition were also observed in later lactation where sow milk at weaning contained increased ($P < 0.001$) concentrations of LA and ALA when supplemental fat was provided by soybean oil rather than choice white grease. Sows provided low EFA with the Control or CWG diets produced milk with greater palmitoleic acid (16:1n-9) compared with sows provided high EFA through SO or Combination treatments ($P < 0.001$). Furthermore, sows provided high EFA also produced milk with a greater proportion of EPA (C20:5n-3; $P < 0.001$), but the proportion of DHA (22:6n-3) was not influenced by dietary EFA intake ($P > 0.05$).

Subsequent reproductive performance

There was no evidence for differences in wean-to-estrus interval, percentage of sows bred by day 7, percentage of sows bred by day 12, or farrowing rate among treatments ($P > 0.10$; Table 9). While there was no influence of lactation diet fat

Table 8. Effects of dietary fat source and essential fatty acid intake on milk composition[1]

Trait	Control	CWG	SO	Combination	SEM	*P*=
Crude protein, %	6.2	5.9	5.9	6.0	0.21	0.670
Crude fat, %	6.2	6.2	6.4	6.7	0.37	0.693
Fatty acids, %[2]						
14:0	4.28[a]	4.11[a]	3.48[b]	3.69[b]	0.137	<0.001
16:0	38.64[a]	35.17[b]	33.71[b]	33.86[b]	0.712	<0.001
16:1n-9	12.57[a]	12.00[b]	9.99[c]	9.41[c]	0.400	<0.001
18:0	3.80	3.87	3.46	3.71	0.142	0.108
18:1n-9	20.90[b]	23.22[a]	19.46[b]	20.73[b]	0.515	<0.001
18:2n-6	12.68[b]	14.00[b]	21.51[a]	19.82[a]	0.615	<0.001
18:3n-3	0.94[b]	1.11[b]	2.80[a]	2.59[a]	0.129	<0.001
20:4n-6	0.36	0.37	0.34	0.30	0.021	0.078
20:5n-3	0.025[b]	0.030[b]	0.050[a]	0.047[a]	0.003	<0.001
22:6n-3	0.010	0.011	0.011	0.010	<0.001	0.316
Other[3]	3.78[b]	4.42[a]	3.47[c]	3.79[b]	0.103	<0.001

[ab]Means within row with different superscripts differ ($P < 0.05$).
[1]A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination). A subset of 10 sows per treatment were randomly selected for analysis of milk composition at weaning.
[2]Represented as a percentage of total milk fat.
[3]Contains 2% or less of the following: 14:1, 15:0, 17:0, 17:1, 18:1*t*, 18:2*t*, 18:3n-6, 20:0, 20:2, 21:0, 22:0, 23:0, 24:0, and unidentifiable fatty acids.

Table 9. Effects of dietary fat source and essential fatty acid intake on subsequent reproductive performance of sows[1]

Trait	Control	CWG	SO	Combination	SEM	*P*
Wean to estrus interval, d	4.7	4.5	4.6	4.7	0.14	0.790
Bred by day 7, %	94.8	95.9	95.1	95.5	0.81	0.749
Bred by day 12, %	95.6	96.4	95.8	96.0	0.74	0.838
Farrowing rate, %	87.9	87.2	88.9	86.8	1.25	0.564
Farrowing performance						
Subsequent litters, *n*	648	637	655	637	—	—
Total born, *n*	14.6	14.6	14.4	14.4	0.15	0.563
Born alive, %	91.2[b]	92.3[a]	91.9[ab]	91.3[ab]	0.42	0.012
Stillborn, %	6.6[a]	5.8[b]	6.3[ab]	7.1[a]	0.35	0.001
Mummy, %	2.1[a]	1.9[ab]	1.7[ab]	1.5[b]	0.16	0.024

[ab]Means within row with different superscripts differ ($P < 0.05$).
[1]A total of 3,451 sows and their litters were used over 28-d experimental periods with 850 to 874 sows per treatment. Experimental treatments contained supplemental fat at 0.5% (Control), 3% (CWG or SO), or 5% (Combination).

source and EFA intake on subsequent litter size, sows previously fed CWG had a greater percentage of pigs born alive (P 0.012) when compared to sows previously fed Control, with sows provided SO or Combination treatments intermediate.

Reproductive performance of sows can be directly influenced by PUFA incorporation into oocyte cell membranes, ovarian follicle and embryonic development, cell signaling for pregnancy recognition and maintenance, eicosanoid production, and modulation of prostaglandin expression patterns (Weems et al., 2006; Wathes et al., 2007; Thatcher et al., 2010). In lactating cattle, implementation of nutritional strategies that increase EFA intake has been observed to improve fertility (Santos et al., 2008; Thatcher et al., 2011). For the lactating sow, follicle development begins during lactation (Soede et al., 2011). Furthermore, the greatest likelihood for sows to enter a negative EFA scenario is during the lactation period when daily EFA intake is limiting and tissue mobilization is required for milk EFA secretion, especially as sows advance in parity (Rosero et al., 2015, 2016a). Thus, dietary modifications to EFA in the lactation period could influence subsequent reproductive performance.

Previously, Smits et al. (2011) observed an increase in subsequent litter size when sows were supplemented fish oil providing n-3 fatty acids during the previous lactation period. Additionally, a dose–response study was completed by Rosero et al. (2016b) to evaluate increasing dietary LA and ALA through blends of canola, corn, and flaxseed oils on subsequent performance of sows. The authors observed reductions in wean-to-estrus intervals and improved farrowing rates for parity 3 to 5 sows, suggesting a positive impact of additional dietary EFA to mature sows. In the present study, average parity of the herd was 4.8. Utilizing the EFA intake recommendations from the retrospective analysis of Rosero et al. (2016b), we were surprised to observe no evidence for differences in subsequent reproductive performance of sows in this older herd. However, this observed response did align with another study that evaluated the comparison of salmon or soybean oil inclusion that provided varying n-3 and n-6 FA profiles in lactation diets where subsequent reproductive performance of sows was not influenced (McDermott et al., 2020).

Additional research may be warranted to understand the mechanisms by which n-3 and n-6 FA influence sow reproductive performance to understand the discrepancies among studies. Furthermore, it is important to consider the likelihood of exacerbated parental EFA deficiency under conditions of extreme heat stress that may occur when lactating sows exhibit reduced feed intake and increased tissue mobilization to support milk EFA secretion (Rosero et al., 2016a; Boyd et al., 2019). In the present study, sows lactated between August 2020 and February 2021. As a result, only a small proportion of sows mated in late summer and early fall may have experienced symptoms of heat stress that could have otherwise affected subsequent reproductive performance.

Conclusions

In summary, sows that consumed diets with high EFA sourced from soybean oil produced litters with greater lactation ADG and piglets with heavier weaning weights when compared with sows with lower LA and ALA intakes. EFA composition of the diet did not influence colostrum and milk macronutrient composition but increasing sow EFA intake did increase LA and ALA content within colostrum and milk. Although litter survivability was not influenced in the first 24 h postpartum or from 24 h to weaning, the modifications to colostrum and milk composition in partnership with elevated sow EFA intakes during lactation supported improved litter performance. Additionally, we did not observe an impact of lactation LA and ALA intake on subsequent sow reproductive or farrowing performance. Due to the advanced parity structure of the herd evaluated in the present study, sows may not have entered an EFA-deficient state, so improvements in subsequent reproductive performance may not have been realizable. Nonetheless, it is important to consider the positive effect of colostrum and milk LA and ALA transfer that supported improved litter growth performance.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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